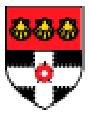

The University of Reading

Numerical Weather Prediction

Single-profile forcing (SPF) of a very high resolution NWP model in the Unified Model

Forecasting Research Technical Report No. 475
Joint Centre for Mesoscale Meteorology Report No. 154

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Abstract

Fog and low level cloud forecasting is crucial for aviation and transport, both commercial and military. Current NWP models can give a broad indication of fog formation and dissipation on scales of a few tens of km, but can provide little detail especially in areas of complex terrain. One-dimensional models for specific locations taking into account the impact of the surrounding orography on the flow have been developed as a cheap solution, but they are unable to treat complex three dimensional flows. A full NWP model running at a horizontal resolution of around 1km (or better) may eventually be required to address the three-dimensional fog forecasting problem in full. But, enhancement of the model resolution to such a scale is presently restrained by available computing power and will not be feasible for many years. However, in the weakly forced situations leading to fog formation, the use of small, local area (e.g. 50 km x 50 km), high resolution NWP model may be a viable alternative.

In this study, we explore the local area NWP model approach, initialising and forcing the model with a time series of single forcing profiles from either a low resolution NWP model, or from a local radiosonde profile. This method of homogeneous single-profile forcing (SPF) allows the model to be run locally with a small volume of input data. The UK Met Office Unified Model (UM) is set up for a 50km by 50km horizontal domain, with real orography and a grid spacing of 1km and 76 vertical levels. The model is initialised and forced with temperature, humidity and wind profiles from a 12km coarse resolution model. In addition, aspects of the current model physics, such as the radiation scheme and microphysics, which have a critical impact on fog formation have also been assessed and optimised. We will show some typical results from a single-profile forcing (SPF) model run, compared with the output from a full NWP model with 1km resolution and observational data.

1 Introduction

The lower part of the atmosphere is crucial for aviation and transport, both commercial and military. In the military context in particular, the presence of fog and low cloud can have a major impact on both airborne and ground based operations. High quality predictions of the formation and dissipation of fog and low cloud, together with associated changes to visibility, would therefore be of considerable operational value in the field. For example, the input of accurate high resolution visibility predictions is essential for the calculations of transmittance performed by the Met Office Electro Optical Tactical Decision Aid NEON.

The formation of fog is a complex and highly non-linear interaction between surface and sub-surface processes, atmospheric radiation, atmospheric turbulence and flows induced by local orography. In particular, very shallow 'drainage' flows due to near-surface cooling on slopes can have a dramatic impact on the local distribution of fog. The dissipation of fog and cloud also involves the complex dynamics generated internally by the fog.

Current NWP models, including those implemented as Crisis Area Mesoscale Models (CAMMs), can give a broad indication of fog formation and dissipation on scales of a few tens of km, but can provide little detail and remain unreliable especially in areas of complex terrain. Linear flow models have been developed and validated for potential incorporation into the CMetS battlefield support system. These, however, are inherently unable to treat the very stable flows associated with complex terrain in the presence of weak large scale flow. The Site Specific Forecast Model (SSFM), a one-dimensional model based on the Unified Model, has been developed as a cheap alternative with this problem in mind, but it, too, is unable to treat complex three dimensional flows.

A full NWP model running at a horizontal resolution of around 1km (or better) may be required to address the three-dimensional fog forecasting problem properly. Enhancement of the CAMMs resolution to such a scale is restrained by available computing power and will therefore not be feasible for many years. However, in the weakly forced situations leading to fog formation, the use of small, local area (e.g. 50 km x 50 km), high resolution versions of the UM may be a viable alternative for particularly sensitive locations.

The potential exists to run such models locally on a high-spec PC. Operationally this could be highly advantageous, not least because it would eliminate the need to send high volumes of forecast data over limited bandwidth communications links. Initial forcing data would, however, still be required for the locally run model. Using the current model nesting regime entails communication of large volumes of lateral boundary forcing data.

An alternative approach would be the development of a homogeneous single-profile forcing method from either global model or local radiosonde data. Such initial data would be of significantly lower volume, facilitating its communication at low bandwidth to the outfield. For the system proposed, aspects of the current model physics, such as the radiation scheme and microphysics, which have a critical impact on fog formation must also be assessed and optimised. This is necessary to ensure their accuracy and reliability in the near surface layers of the atmosphere, where fog formation occurs, when the model is run at considerably higher horizontal and vertical resolution than at present.

The purpose of this document is to describe the implementation of a single-profile forcing approach in the Unified Model (UM) and to show the application of the approach in a case study of fog formation for a small domain in the southern UK. In section 2 we explain how single-profile forcing data are interpolated/extrapolated to create the 3-D initial forcing fields. Section 3 discusses the different forcing options. In sections 4 and 5, we present the numerical results with discussion and conclusions.

2 Generation of a high resolution 3-D forcing data from a single forcing profile

Well-posed and accurate initial and boundary forcings are the key to a succesful forecasting model. In this section we describe how to derive the initial/boundary forcing profiles from a coarse resolution driving model.

We have, as input, a set of model forcing profiles ϕ_f, on a given set of levels η_f with known heights $z(\eta_f)$. These data represent the average value on the forcing model levels η_f of the large scale state over our small scale domain. In a practical case, the top level is flat over our small scale domain, while the bottom level may not be over the land. Our small scale model has a set of non-horizontal levels η_m with known heights $z(\eta_m)$. Since they are non-horizontal, the input data cannot correspond exactly to model level data. The model is forced with the prognostic variables winds (u, v), potential temperature θ and relative humidity q. In this section we describe how to create the 3-D forcing field for these prognostic variables from a single forcing profile ϕ_f, here $\phi = (\theta, q, u, v)$.

2.1 Temperature, moisture and horizontal winds (θ, q and (u, v))

Options

In general, the forcing models are coarse resolution models, and as described before, the forcing profile ϕ_f is generated by averaging the forcing model's output ϕ onto the forcing model levels $\eta_f(k)$ over our small high resolution model domain. In this study the forcing model has 38 vertical levels $\eta_f(k)$ and our small domain high resolution model has 76 vertical model levels $\eta_m(l)$. Here l is the vertical index for the model level, and k is the index for forcing profile's vertical level. From the input forcing profile data set $\{\phi_f(z), z(\eta_f), \eta_f(k), k = 1, 2, \cdots, 38\}$ we wish to create a 3-D initial model forcing data set $\{\phi_m(z), z(\eta_m), \eta_m(l), l = 1, 2, \cdots, 76\}$. When the model orography is the same as the forcing model orography, simple linear interpolation in the vertical should be used. However, since the problem we are solving here is a high resolution model over a small domain, a problem arises at the orographic surface. In general, the model's first level $z_{orog}(i, j)$ is not the same as the forcing profile's first level z_{iorog} i.e. $z_{orog}(i, j) \neq z_{iorog}$, where (i, j) is the index for the horizontal discretisation. Three options are considered here on how to create a 3-D initial model forcing field $\phi_m(z)$ (see Figure 1 for a schematic diagram of the three options).

Option 1. Terrain-following by simply interpolating the forcing data on the model levels.

$$\phi_m(i,j,l) = \text{interp}[\phi_f(k), \phi_f(k+1)]$$

where $\eta_f(k) < \eta_m(l) < \eta_f(k+1)$. If we do this for θ, we are effectively assuming that the η_m-surfaces are isentropic. This is not that unreasonable and, indeed, is an ideal sought when designing the vertical grid. Given a terrain following grid near the surface tending to a flat one at the top, we are stretching the grid downwards over valleys and compressing over hills. This can be very good for gentle terrain but unrealistic for steep mountains where in practice the flow would go around, not over.

Option 2. Constant with height – we assume the input profile is fixed on height levels. Where orography is larger than the forcing height $z_{orog} > z_{iorog}$, we do linear interpolation as in option 1,

$$\phi_m(i,j,l) = \text{interp}[\phi_f(k), \phi_f(k+1)]$$

but, this time on the height levels, $z_k < z_l < z_{k+1}$, where z_l is the height at model level l, and z_k is the height of forcing data at forcing level k. Where orography is less than the forcing height $z_{orog} < z_{iorog}$, we have to invent an atmospheric profile below the forcing bottom surface z_{iorog}.

Option 3. A combination of the above 2 options – we assume an input profile fixed in height above a certain level, terrain-following near the surface with a gradual stretching in between. This is the option used in this study, and we describe the details below.

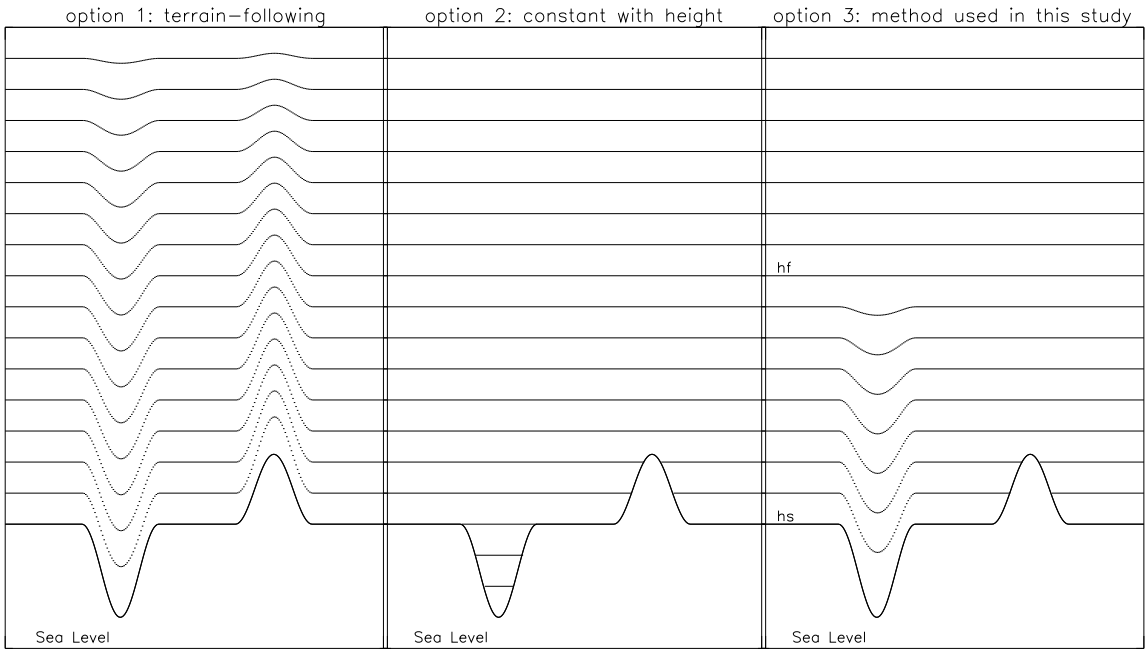

Figure 1: Schematic diagram of a cross-section of the 3-D output data field for each option discussed in Section 2.

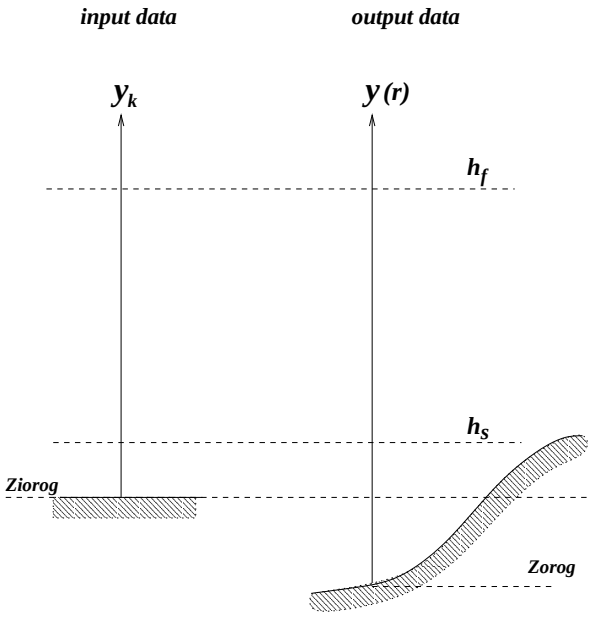

Figure 2: Schematic diagram of the input and output data coordinates. The input data from z_{iorog} to h_f are linearly stretched to produce data between z_{orog} and h_f. If $z_{orog} \leq h_s$, copy data below h_f into the forcing profile. Here $z_{orog} = r_\theta(0) - a$ is the model orography, a is the Earth radius and $h_s = \{z_{iorog}, h_f\}$.

Method used in this study

We need three input parameters: z_{iorog} is the height of the orography in the input data, h_f defines the height, below which input data are stretched. $h_s = \{z_{iorog}, h_f\}$ is the height defined as when orography z_{orog} is below h_s, the stretched data are used (see Figure 2). Having defined these parameters, we then:

1. Interpolate the input profiles linearly in height at every horizontal point (option 2) to generate the 3-D fields, $\phi_m(i,j,l)$, $(\phi = (\theta, q, u, v))$. Note this generated the 3-D fields for every points where the orography is higher than input orography $z_{orog} > z_{iorog}$. Now we need to create the 3-D fields for where the input orography $z_{orog} < z_{iorog}$.

2. At every horizontal point (i,j), calculate ϕ_{temp} by linear interpolation of input data in y space. Assign variable y to input data

$$y_k = \frac{z - z_{iorog}}{h_f - z_{iorog}}$$

then for each output model level data point compute

$$y\,(r_\theta) = \frac{r_\theta - r_\theta(0)}{h_f + a - r_\theta(0)}$$

and interpolate from input data linearly in y space. Here r_θ is the model levels, a is the Earth radius and $z_{orog}(i,j) = r_\theta(i,j,0) - a$.

3. If $z_{orog} \leq h_s$ copy ϕ_{temp} into ϕ_m wherever $r_\theta - a < h_f$.

When $h_s = h_f$, option 3 produces a terrain-following 3-D field like option 1. In this study we set $h_s = z_{iorog}$.

An analogous procedure is followed for θ, q and (u, v). Thus from the single-profile forcing data, we have generated the full 3-D initial forcing.

2.2 Hydrostatic approximation of the initial pressure (and density) field

The initial pressure field is computed using the hydrostatic approximation written as:

$$\frac{\partial p}{\partial z} + \rho g = 0 \tag{1}$$

in z co-ordinates. This equation can be transformed to

$$\frac{\partial \Pi}{\partial \eta} + \frac{g}{C_p \theta_v} \frac{\partial z}{\partial \eta} = 0 \tag{2}$$

in the η coordinate system, $\eta(z_s) = 0$, $\eta(z_T) = 1$, and Π is the Exner function (normalised pressure), defined as,

$$\Pi = (\frac{p}{p_0})^\kappa \tag{3}$$

while $\kappa = \frac{R}{C_p}$, R is the gas constant for unit mass of dry air, $p_0 = 1000$mb is a reference pressure, and θ_v is the potential temperature for moist air.

We generate the 3-D pressure field by integrating equation (2) from the orographic surface to the top of the domain.

$$\Pi(i,j,l) = \Pi(i,j,l-1) - \frac{g}{C_p} * (r_\theta(i,j,l) - r_\theta(i,j,l-1))/\theta_v(i,j,l-1) \tag{4}$$

and,

$$\theta_v(i,j,l) = \theta(i,j,l) * (1.0 + re_epsilon * q(i,j,l)),$$

$$re_epsilon = 1.0/\epsilon - 1.0,$$

where $\epsilon = 0.62198$ is the ratio of molecular weights of water and dry air, and at the orographic surface,

$$\Pi(i,j,0) = (\frac{p_{surface}}{p_0})^\kappa.$$

3 Forcing methodology

We have described in the previous section how to set up the initial forcing profiles. In this section, we discuss some problems associated with the single-profile forcing mechanism, and describe the techniques used to overcome those problems.

3.1 Mass conservation and orography at the lateral boundaries

Before we apply a single-profile forcing to a model with real topography, we must consider the issue of mass conservation.

Consider single-profile forcing in a horizontal domain D with a boundary S. The vertical dimension in z-coordinates is $z_s < z < z_T$, where $z_s(x, y)$ is the topography, and z_T is the "top" of the atmosphere. This defines a three-dimensional domain R.

Conservation of mass for the three-dimensional domain R yields

$$\frac{\partial M}{\partial t} = -F\,, \tag{5}$$

$$\text{where} \quad M = \int_R \rho\, dV\,,$$

$$\text{and} \quad F = \int_{\partial R} \rho \mathbf{u}.\nu\, dS\,.$$

Here ρ is the fluid density, $\mathbf{u}$ is the three-dimensional vector, and ν is the unit outward normal to the boundary ∂R of R, M is the total mass and F is the flux of mass out of the domain. Note that at the bottom on the topography, and at the top, we must have that $\mathbf{u}.\nu = 0$ since there can be no flow through these boundaries. Next, separate out the z-integration terms in these integrals. Thus

$$M = \int_D (\int_{z_s}^{z_T} \rho\, dz) dx dy\,, \tag{6}$$

$$F = \int_S (\int_{z_s}^{z_T} \rho\, dz) \mathbf{U}.\mathbf{n}\, d\sigma\,. \tag{7}$$

Here σ is arc-length on S, and $\mathbf{n}$ is the unit outward normal to S. Note that $\mathbf{n}$ is horizontal, and on S, we can set $\mathbf{u} = \mathbf{U}$ as a constant.

The problem is that from the nature of the forcing F is essentially already known, and unless it is zero, the mass will change. To show this, use the hydrostatic approximation

$$\frac{\partial p}{\partial z} = -g\rho\,,$$

to estimate the density in these expressions, where p is the pressure. Thus

$$M = \frac{1}{g} \int_D (p_s - p_T)\, dx dy\,, \tag{8}$$

$$F = \frac{1}{g} \int_S \mathbf{U}.\mathbf{n}\, (p_s - p_T)\, d\sigma\,, \tag{9}$$

$$\text{and} \quad p_s(x, y) = p(x, y, z_s)\,.$$

Here, p_s is the pressure at the bottom, evaluated on the topography, and p_T is the *constant* pressure at the top, $z = z_T$; here p_T can be regarded as known, say $p_T = 0$ for instance. Since $\mathbf{U}$ is a *constant*, F is in effect proportional to an averaged pressure gradient across the domain D. This should be zero, but due to the topography, may not be. Thus the mass M will change with time.

Clearly, in order to remedy this, a correction is needed. One possible solution is to adjust the surface pressure so that $F = 0$ at every time step. In effect, this ensures that there is no net pressure gradient across the domain.

For instance, suppose that the domain D is rectangular,

$$D : x_1 < x < x_2\,, y_1 < y < y_2$$

$$\text{and so} \quad S : y = y_1, y_2 \,\text{with}\, x_1 < x < x_2\,,\ x = x_1, x_2 \,\text{with}\, y_1 < y < y_2\,.$$

The imposed velocity field is then $\mathbf{U} = (U, V)$. Then the expression above for F becomes

$$F \;=\; U \int_{y_1}^{y_2} \Delta_x p_s \, dy \;+\; V \int_{x_1}^{x_2} \Delta_y p_s \, dx\,,$$

$$\text{where} \quad \Delta_x p_s \;=\; p_s(x, y_2) - p_s(x, y_1)\,,$$

$$\text{and} \quad \Delta_y p_s \;=\; p_s(x_2, y) - p_s(x_1, y)\,,$$

are the pressure jumps, evaluated on the bottom topography, across the domain in the x, y-directions respectively. If there was no topography, these should be zero. This leads to the first method of fixing the problem, That is, set the orography around the boundary to be the same as the forcing orography data which is a constant at every point around the boundary.

$$z_{orog} = z_{iorog}\,. \tag{10}$$

Here, z_{orog} is the model orography and z_{iorog} is the input forcing orography (see Figure 1). This ensures $F = 0$ at every time step, and therefore mass is conserved.

Another way to deal with this problem is to insist that M is a constant in (8). We will make the right hand side of (8) constant by relaxing the mean surface pressure value to its forcing value. Let

$$p_s = \bar{p}_s + \Delta p_s$$

where $\bar{p_s}$ is the mean surface pressure:

$$\bar{p}_s \;=\; \frac{1}{D} \int_D p_s \, dxdy\,.$$

then at every time step, we relax the mean surface pressure $\bar{p}_s$ to the mean forcing surface pressure $\bar{p}_{sf}$:

$$\bar{p}_{sf} \;=\; \frac{1}{D} \int_D p_{sf} \, dxdy\,.$$

In summary, there are three options to deal with the mass conservation problem/issue here. First, modify the orography around the boundaries to be the same as the forcing orography data. Second, modify flow (wind) field at the inflow and out-flow boundaries to balance the mass, but it's remains a question how this can be done. The third method is to adjust the pressure field as described above. However, in practise, it is not alway easy to obtain the surface pressure forcing data. In this study, we adopt the method of setting the orography around the boundaries to be the same as the forcing orography data. The lateral boundary forcing rimwidth is set to 4, and at this forcing zone the orography is set to a constant as described in (10). Further we take another 4 points to linearly smooth the constant orography at the lateral boundary and the actual orography at the inner domain.

3.2 Forcing options

We wish to force the model in such a way that equivalent domain averaged θ, q and (u, v) track, to an acceptable tolerance, the time series of input data. The general options for homogeneous forcing proposed here are:

A) Boundary forcing

For the small model domain (50 x 50) used in this study, we set the forcing boundary rimwidth to 4, with a weighting of 1.0, 0.75, 0.5 and 0.25. Replace, at each time step, model data on the boundary (more generally in a boundary zone) with equivalent data derived from the forcing.

B) Relaxation in the interior of the domain

At each timestep add a correction to each level equal to the difference between the 'horizontal' domain average of the model and the forcing data at that level. The same correction profile (possibly adjusted for orography) is added across the whole domain (uniform forcing). A refinement is to add only a fraction, $\Delta t/\tau$, of the correction each timestep, thus forcing a tendency to correct the mean but not guaranteeing that the mean is exactly correct i.e.

$$\phi_{incr} = (\bar{\phi}_f - \bar{\phi})\Delta t/\tau \tag{11}$$

here ϕ represents variables (u, v), θ and q; ϕ_{incr} is the model field increment after each time step; $\bar{\phi}_f$ is horizontal domain average of forcing data, and $\bar{\phi}$ is horizontal domain average of the model data, τ is the relaxation time scale. Thus

$$\phi = \phi + \phi_{incr}$$

3.3 Hydrostatic pressure adjustment for divergent flow

After setting the orography at the boundaries to a constant, together with the uniform forcing field, we have conserved mass for a non-divergent flow. Clearly, a correction is needed here to accommodate the divergence in the large scale flow. Several steps are required for this correction:

1. At the end of every time step, at every horizontal point, integrate the pressure field downward using the hydrostatic assumption from the top of the domain, to generate a hydrostatic pressure field on every model level.
2. This hydrostatic pressure field is then linearly interpolated onto the forcing data levels at every horizontal gridpoint.
3. This is then compared with the forcing data to obtain the difference.
4. Interpolate the differences back to the model levels.
5. Finally, adding the differences calculated from above to the model pressure to adjust it's mass balance.

4 Case study

We chose the 9-10th Dec 2003 fog case for this study. This is a classic case (so-called 'pea-souper') in which fog persisted over parts of East Anglia, Southern England, Southern Midlands and East Wales. Observation data for visibility (fog) were available at Benson and High Wycombe over a 24-hour period. We wish to compare the SPF model with a 3-D nested model result.

4.1 Experimental set up

As mentioned before, the model should be forced in such a way that the equivalent domain-averaged θ, q and (u, v) track, to an acceptable tolerance, the time series of input data. There are number of forcing methods we are going to look at in this study:

1. A standard 3-D nested model, with a nesting ratio of 12/4/1km. We set up two benchmark reference runs, a 300×300 1km high resolution run (labeled **Ref** hereafter), and a 50×50 1km high resolution run (labeled **Ref_50** hereafter), to compare results with the single-profile forcing runs.
2. Single-profile forcing, forced by the initial values only (labeled **Init** hereafter). The lateral boundary values are fixed to their initial values in this case.
3. Single-profile forcing, forced by the initial values and the time-varying lateral boundary forcing (labeled **Full** hereafter).
4. Single-profile relaxation forcing (labeled **Relax** hereafter).

Numerically, the following procedures must be followed:

1. Take the 12km coarse resolution forcing model's start dump as our start dump.
2. Create ancillary files using ancillary creation script on the NEC. The ancillary files used in this study are land-sea mask, orography, ozone and *ite* land-use, on our high resolution domain (50×50 horizontal grid points and 76 vertical levels).
3. Reconfigure dump with these ancillary files to our high resolution domain.
4. Take the 12km coarse resolution forcing model's hourly output of θ, q, (u, v), and the pressure at the sea level p_{msl}, and average them over the high resolution small domain's model levels, to create the single column forcing profiles.
5. Build an idealised namelist contains those profiles, an example namelist is in Appendix A.

As discussed before, to apply single-profile forcing to a model with real orography would cause a mass imbalance in the computational domain. In order to conserve mass, we set the orographic height at the lateral boundaries (LBCs) to the height of the orography in the input

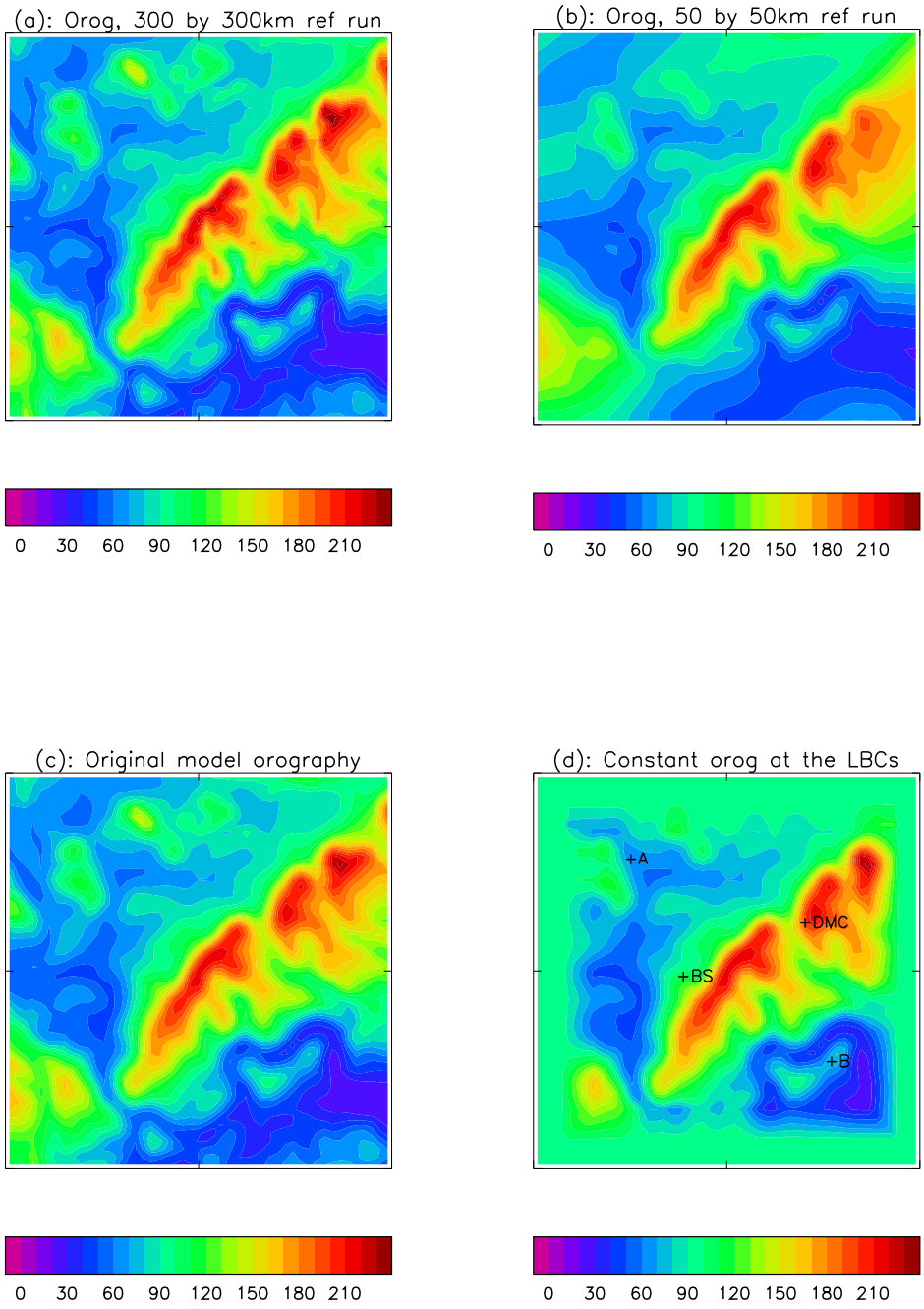

Figure 3: Orography of the model domain (a): 300km by 300km reference run orography; (b): 50km by 50km reference run orography; (c): original orography of the single-profile forcing model domain; (d): after setting the boundary height to a constant value. **A** and **B** are the two end points of the cross-section for Figure 5. The two observational sites are marked as **BS**: Benson and **DMC**: DMC (High Wycombe)

profile $z_{LBC} = z_{iorog}$. In Figure 3 we show contour plots of orography for different models: (a) the 300km by 300km reference run orography, which has 1km resolution everywhere in the targeted 50km by 50km inner domain; (b) orography for the 50km by 50km reference run, which was blended with 4km resolution orography at the boundary zones, (c) the input, unchanged orography for this study, (d) the orographic height at the lateral boundaries (LBCs) is set to the height of the orography in the input profile, 97m in this case. Figure 3 shows that the largest difference is around the lateral boundaries (LBCs). Since the high ground is positioned in the middle of the domain, the representation of the hills is quite good. However, due to the modification of orographic height at the lateral boundaries the extent of the valleys in the model domain is significantly reduced. We have also introduced an artificial enclosed valley/basin in the lower right-hand side of the domain, where there should be a valley open at the right-hand side of the boundary. However, due to the boundary blending the 50km by 50km reference run also has some smoothed orography in the same region, and thus also fails to achieve the very low values in the orography field. Since fog mostly formed in the valley areas, these discrepancies could have some impact on our numerical results.

4.2 Numerical results and discussions

Results are compared with two full nested reference runs, a 300km by 300km large domain reference run (Ref) in Figure 4) and a 50km by 50km domain run (Ref_50). Three single-profile forcing model runs with forcing methods Full, Init and Relax were carried out for this study.

a) Full: The full LBC forcing run , in which time varying LBC forcings are used.
b) Init: Initial forcing only run, in which LBC forcings are fixed to the initial values.
c) Relax: The relaxation forcing run,‘ like (a), but forcing also applied to the whole model domain with a relaxation method.

In Figure 4 we show the comparison of the model averages of pressure at mean sea level; surface pressure; visibility at 1.5m; specific humidity at 1.5m; temperature at 1.5m; and dewpoint temperature at 1.5m. Note that only the inner 30km by 30km area is used to calculate the area average, the LBC forcing and orography modification zones are excluded.

As expected, Ref and Ref_50 are in good agreement. But it is clear that the relaxation forcing run (Relax) failed to get good agreement with the reference runs in all fields. By contrast the LBC forcing runs (Full and Init) give a satisfactory performance. In the pressure fields, the LBC full forcing run (Full), is in general good agreement with the reference runs, while as expected the LBC initial forcing only run (init) keeps to the mean value of reference pressure. In both LBC runs, fog only starts to form after 6 hours of the forecasting time, and after 7 hours, the visibility agreement is good, but is better for the full LBC forcing case. However after the fog forms, both temperature and specific humidity tends to be higher in both LBC runs when compared with the reference. Note that in the reference runs, fog has already formed at the begining of the run, but the LBC forcing runs need to spin-up. Also, it should be noted that in the reference run fog first forms in the eastern valley and then spreads, but in the single-profile forcing run this effect is essentially eliminated. To some extent, this accounts for the lag in the spin-up particularly apparent in the visibility plot.

These discrepancies are partially associated with the initial forcing field, (described in

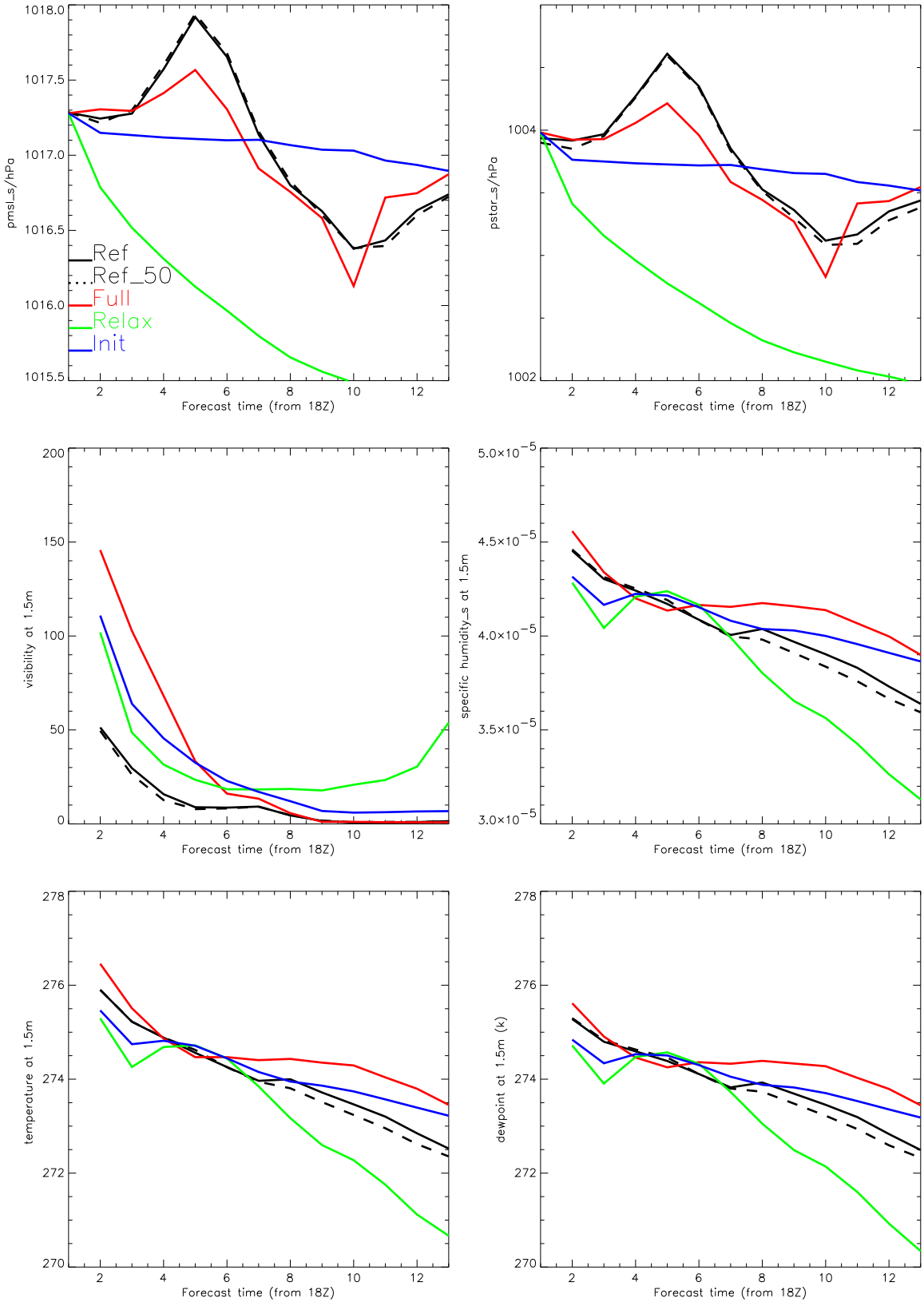

Figure 4: Comparision of model average.

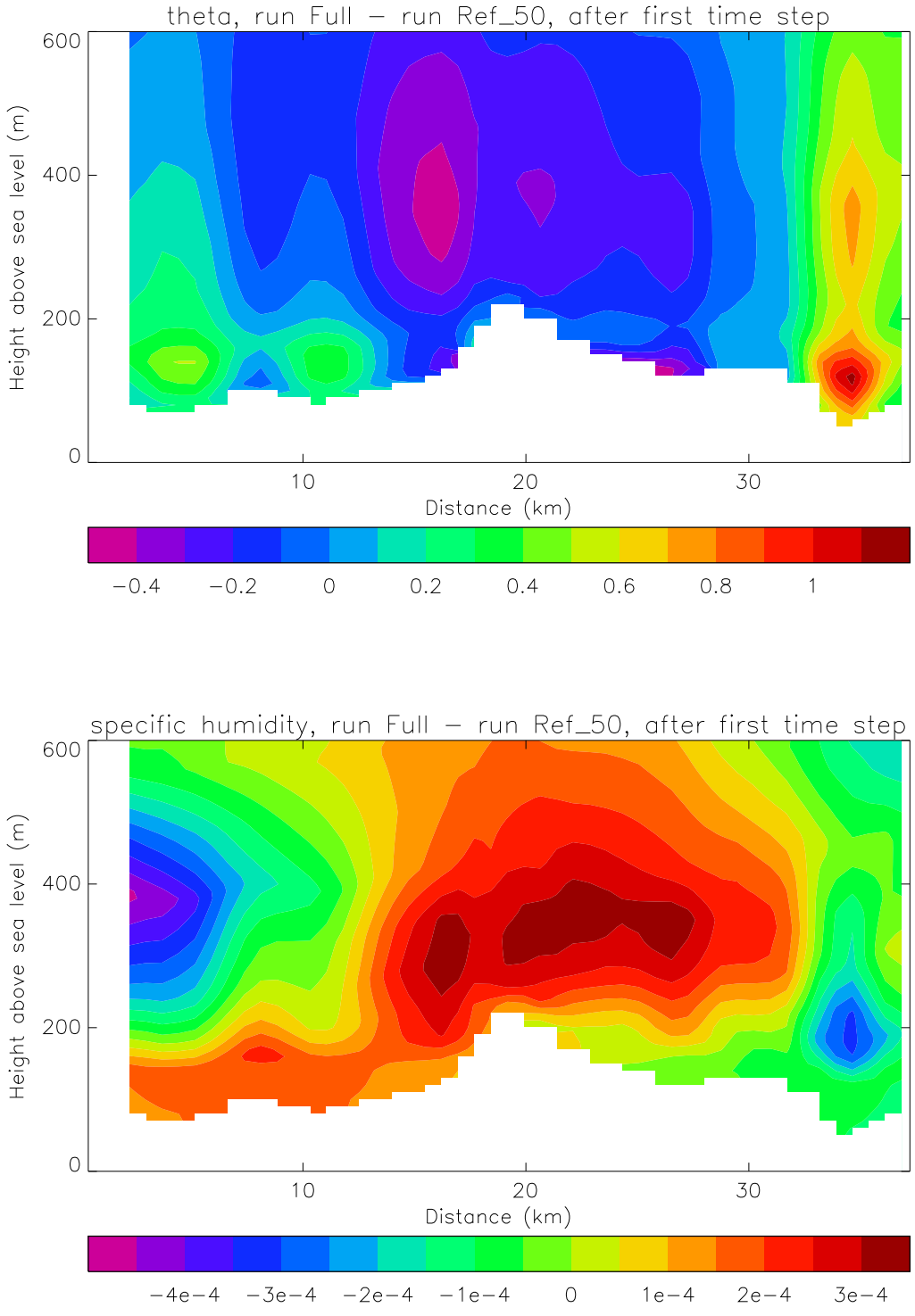

Figure 5: Temperature and specific humidity differences (Full-Ref_50) at model initial time.

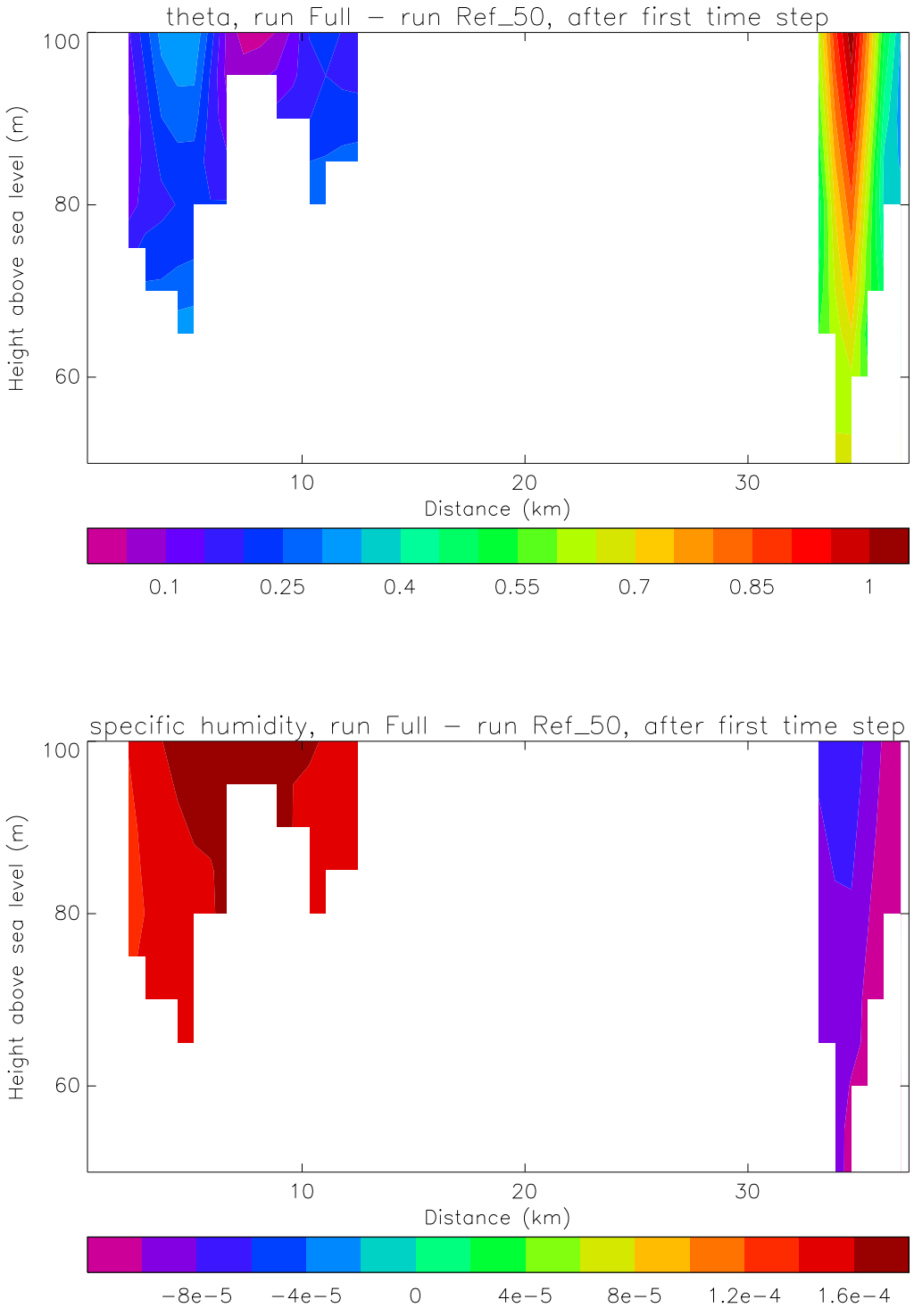

Figure 6: As in Figure 5 but only for the height below 100m.

section 2.1), since we are using a single-profile forcing data to generate the 3-D initial fields. For the forcing data in the valley area, where the orography is below the first available forcing data level (z_{iorog}=97m in this case study), we stretched the single-profile forcing data as described in section 2. To examine any possible impact, we take a close look at the initial forcing field (i.e. the results after the first time step) along a cross section between the points A and B marked on Figure 3. In Figure 5 we shown the model difference between the LBC full forcing run (Full) and the reference run (Ref_50). We see that, in the region above 250m (i.e. above highest topographic surface level), there is a clear bias in both temperature and humidity, as expected, with cooler more humid air over the hill, and warmer less humid air over the valleys. This is because, over the valleys, the initial data has been stretched.

Next let us recall that the forcing data surface height is z_{iorog}=97m, and so, in Figure 6, we show the difference in the valley regions, below this level. The temperature bias is again clearly seen, with warmer air in these valleys as expected from the stretching of the initial data. However, the humidity signal is not clear in this plot, since the bias shows more humid air in the western valley, and less humid air in the eastern valley. To clarify this, in Figure 7 and Figure 8 we plot the specific humidity for both the reference run (Ref_50) and the LBC full forcing run (Full). We see in Figure 7 that in the reference run there is a weak humidity inversion at low levels in each valley, consistent with the fact that in this reference run the fog has already formed. But in the LBC full forcing run, the averaging and the stretching of the initial data has significantly altered the initial humidity profiles at these lower levels, and we now see a more significant humidity inversion at a slightly higher level. This is consistent with what is expected in the early stages of fog formation, and this difference with the reference run weakens somewhat as the LBC full forcing run spins up. Also, note the significant difference in the humidity between the two valleys in the reference run, with Thames Valley on the eastern side being more humid, which is not replicated in the full LBC forcing run, as expected due to the single-profile forcing. In Figure 8, we show the analogous initial humidity profile to those shown in Figure 7, but up to a height of 600m. We see that, as expected, the processing of the initial profile for the full LBC forcing run produces a profile which is more spatially uniform than that for the reference run.

Next, we compare the basic model output after one hour of the run. In Figure 9 we show the surface pressure fields, and temperature and specific humidity at 1.5m. We can see that there is quite a degree of sensitivity. The domain size, model orography and the initial forcing all play an important role. The two reference runs are in gerenally quite good agreement, but some discrepancies remain in places, notably where the orography is not the same. The full LBC forcing run is in reasonable agreement with both reference runs, but the initial-forcing only LBC run has notably less agreement.

In Figure 10 we compare the LBC forcing runs (full and the initial forcing only runs) visibility after 7 hours with the reference runs. Both failed in the outer LBC forcing zone (where the orography is set to a constant, not shown in Figure 10), with no fog forming there at all. Otherwise, in the inner (42km by 42km, the region shown in Figure 10) domain, there is reasonable agreement, with thick fog forming in the valleys. In Figure 11, we again look at the cross-section between A and B for the potential temperature and specific humidity, but now after 7 hours, we see there is good general agreement between the reference and the full LBC forcing runs, for the overall pattern, but some small discrepancies remain in the valleys (note the slight difference in colour-coding scales for the two cases).

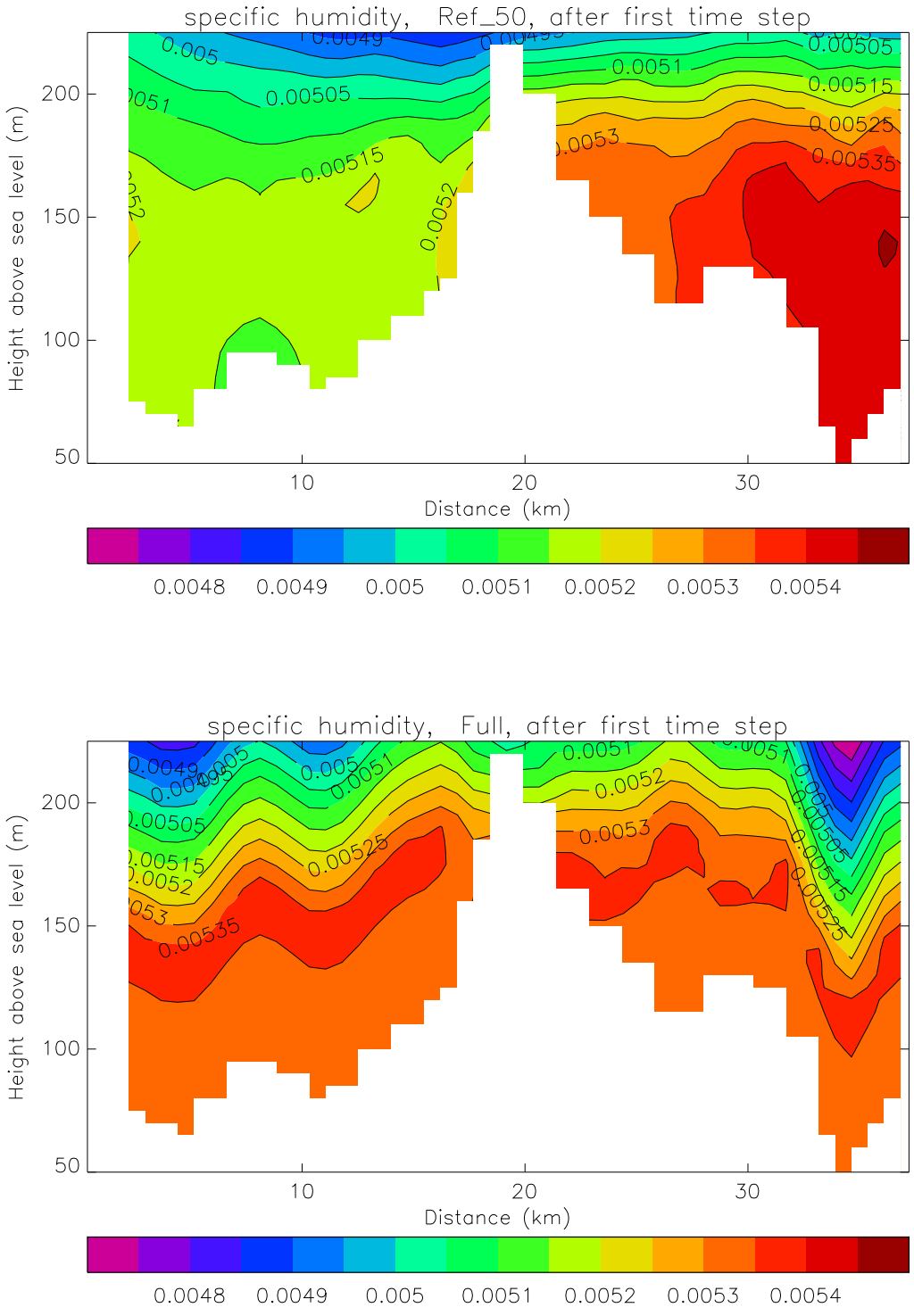

Figure 7: Specific humidity at model initial time.

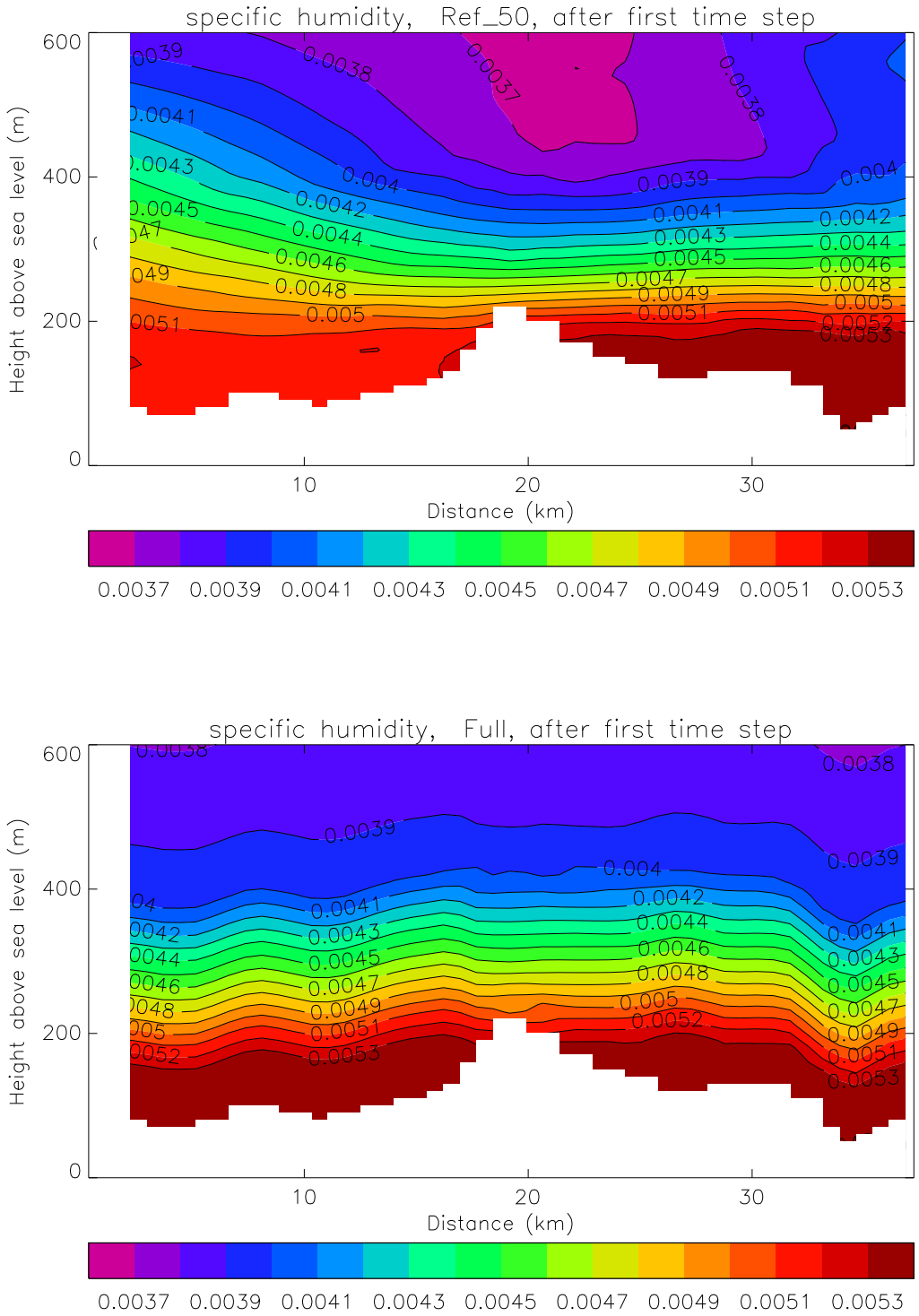

Figure 8: As in Figure 7 but for a height up to 600m.

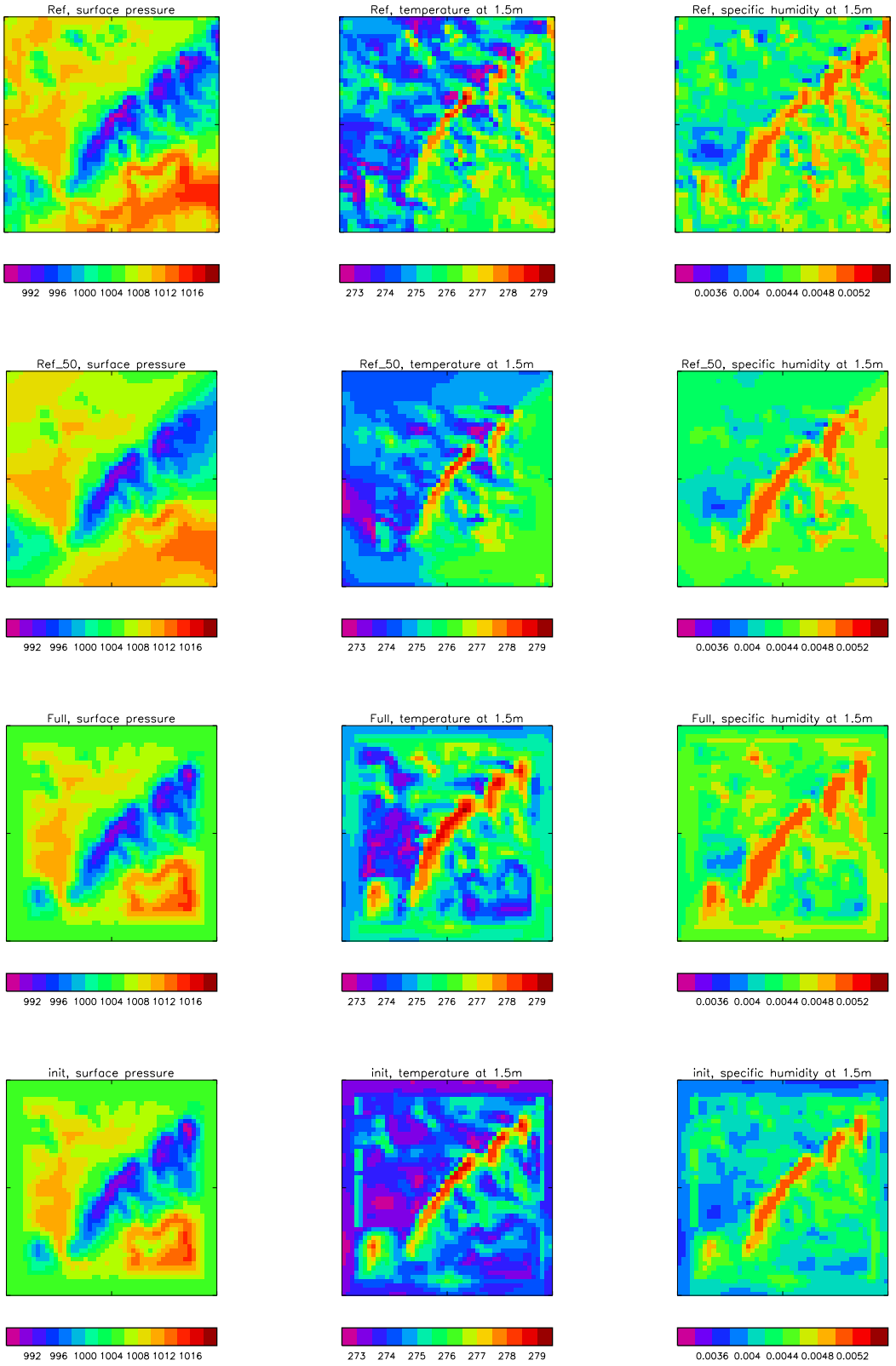

Figure 9: Contour plots of model variables at 20Z on 09/12/2003 (forecast time, from 18Z). Four panels from top to bottom are: the 300km × 300km reference run, the 50km × 50km reference run, the full LBC forcing run, and the initial forcing only run.

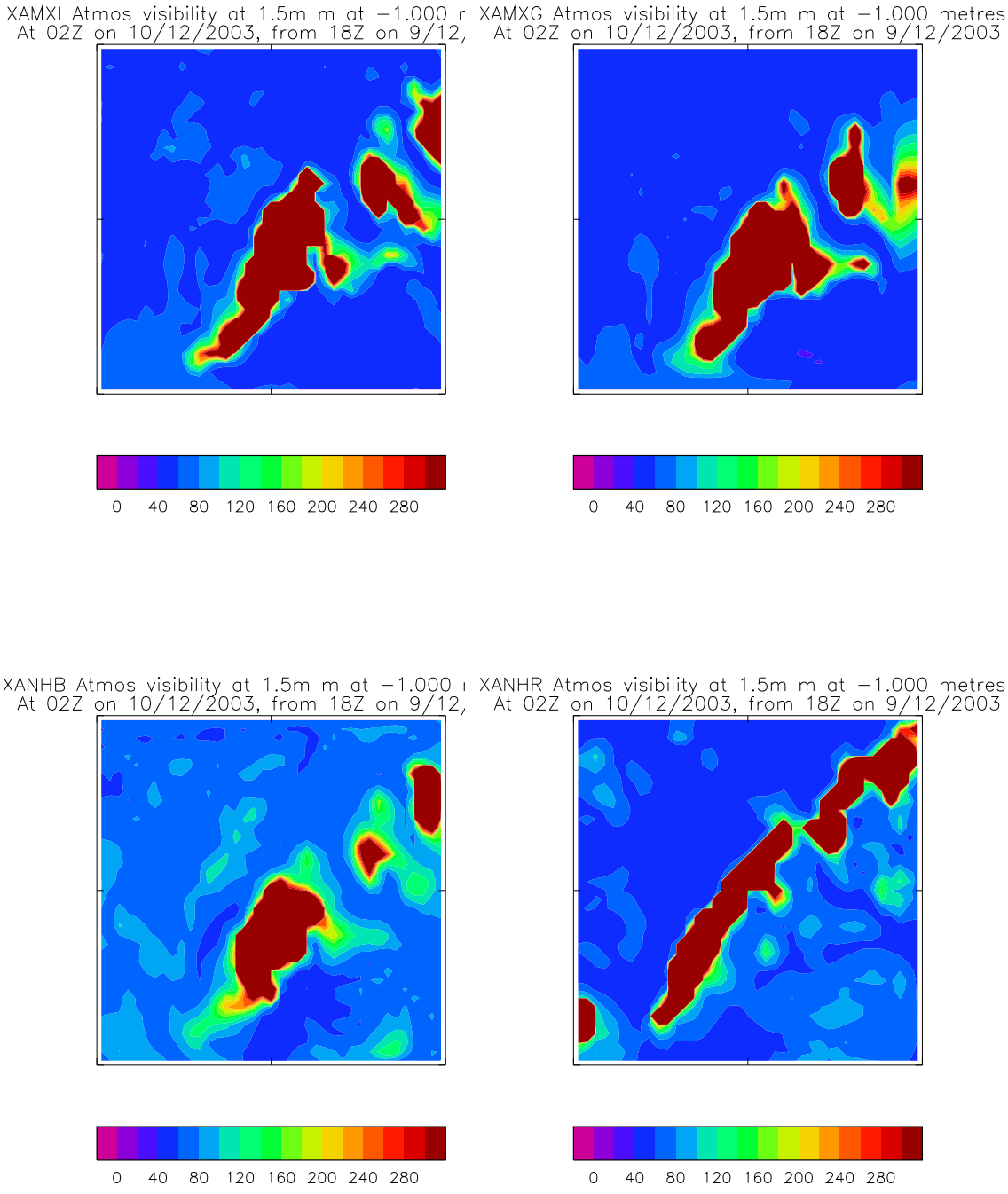

Figure 10: Contour plots of model visibility at 02Z on 10/12/2003 (8 hour model forecast time). Top two panels from left to right are: the 300km × 300km reference run *Ref* and the 50km × 50km reference run *Ref*_50. and the bottom two pannels from left to right are: the variable full LBC forcing run and the initial forcing only run.

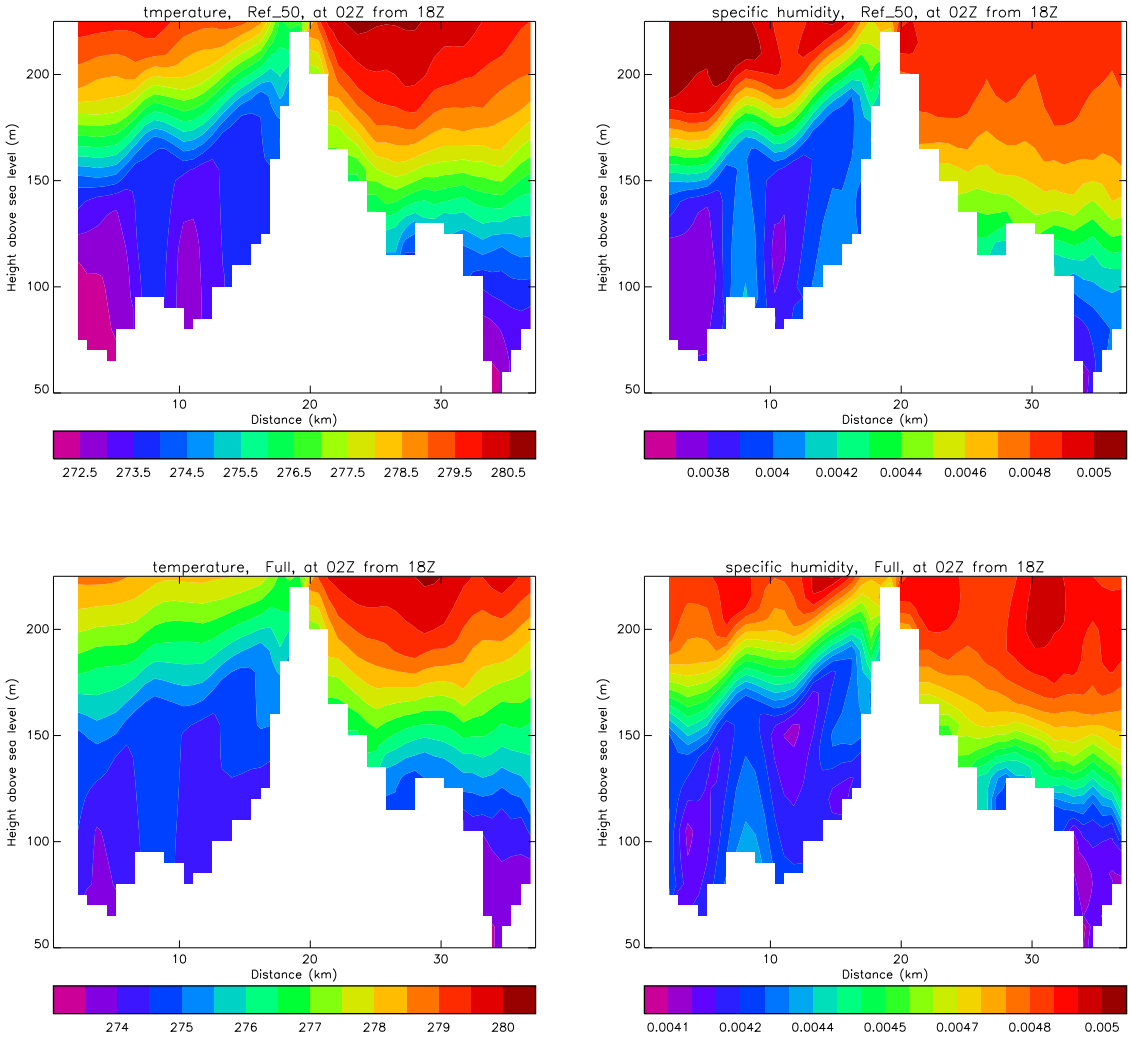

Figure 11: Cross section temperature and specific humidity at 02Z on 10/12/2003 (forecast time, from 18Z 09/12/2003).

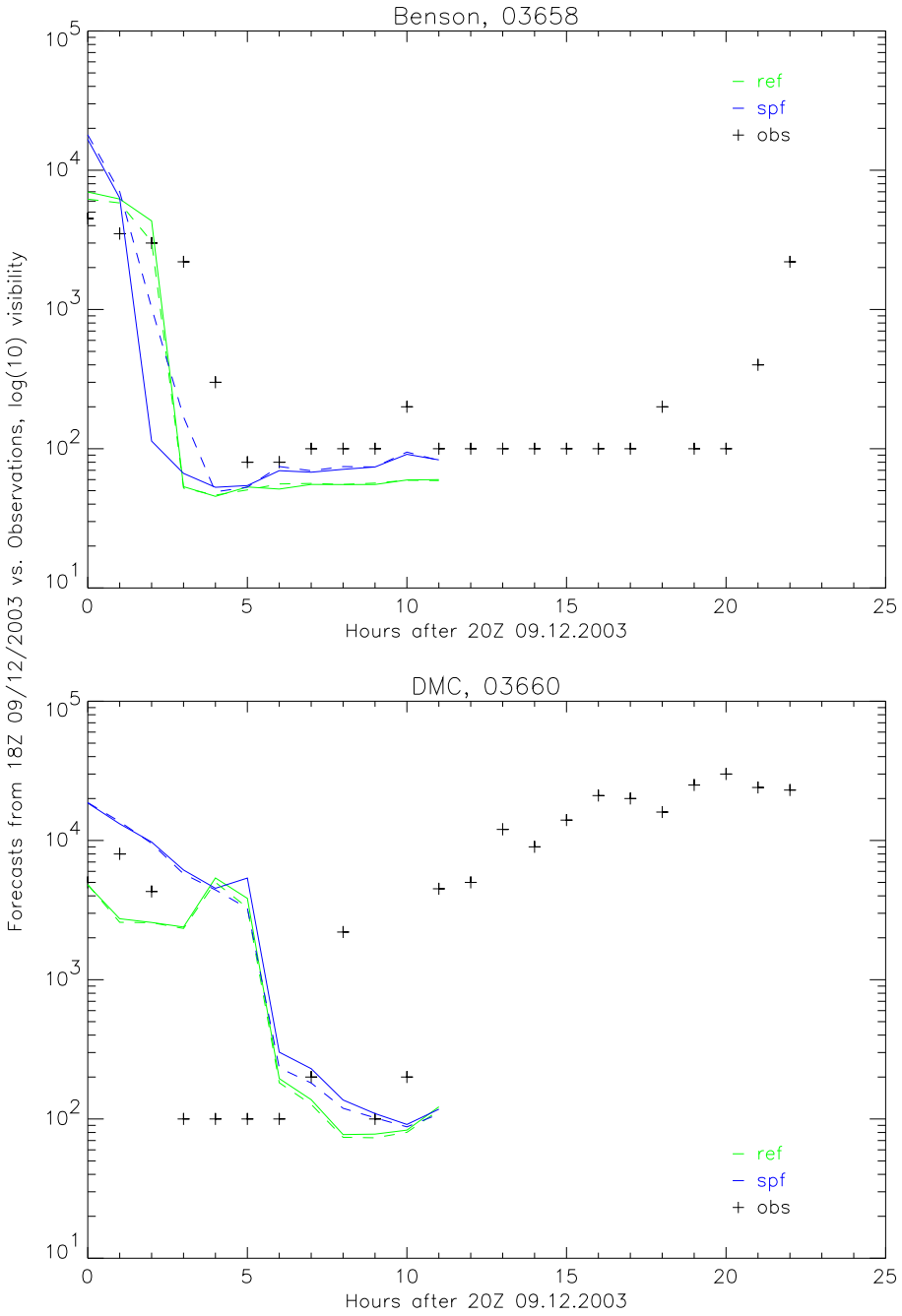

Figure 12: Visibility at Benson and DMC (High Wycombe) observational stations. The green lines are from the 300km × 300km reference run, the blue lines are from the single-profile full forcing model *Full*. The crossed line is the observation, the solid line is the average from nearest 5 points, and the dashed line is the result from the nearest grid point.

Finally, in Figure 12, we compare the model visibility with observations, at two stations, Benson and DMC (High Wycombe). For the purpose of forecasting fog at specific sites, the single-profile forcing model does just as well as the full 3-D nested model at the same resolution. However, more case studies of this kind are needed.

5 Conclusion

Compared with the full 3-D nested model, the single-profile forcing model is easy to use, easy to set-up, and gives a satisfactory performance. However, the test case we have used here is a fog case, and so throughout the run, we have very weak and near uniform wind fields. Further, we only need to run our model over a very small domain. Indeed, these are the limitations of a single-profile forcing model, small domain size and a near uniform wind field.

When setting up the initial profiles and the time-varying forcing profiles, only the variables θ, q and (u, v) are used. Other important variables for fog study, such as soil moisture and soil temperature were not set up in the forcing profiles. Their initial values are taking from the start dump. This is perhaps why the spin-up time is rather long in the fog generation (see the visibility plots in Figure 4). Further, the method used in this study to generate the 3-D initial forcing fields is not the only option. When setting up a new model domain, all options discussed in section 2.1 should be considered for that domain. In this study, we set the constant orographic height at the LBCs to the forcing model average. But a different value, eg. the lowest domain orographic height, might be chosen.

Limitations

As discussed before, although the model performed well compare with a full 3-D nested model. There are limitations due to the nature of the forcing technique.

1. Since the orography at the forcing boundaries was set to a constant, the model domain should not include the largest orography variation at or close to the lateral boundary. Careful consideration is needed when choosing the locations to set up the model domain.

2. The method is designed for fog study, and so the horizontal wind across the domain should be weak and near uniform.

3. The model domain should be small due to the uniformity of the forcing. Even in this case study, it has failed to capture the contrast of the valleys.

Future work

Further study is needed to improve the initial and LBC forcing terms. In this study, forcing was take from a 12km coarse resolution, averaged over the domain. Alternatively, a single representative point, e.g. a valley point, could be used, and hence have the advantage of data covering the whole vertical domain. One other area which could benefit a further study is

that of the relaxation forcing method. In this study, at every relaxation forcing time step, the model average on the model levels were computed to compare with forcing data. This is fine for an idealised flat orography case. But perhaps it is not suitable for an orographic study, since the model variables vary significantly across the model levels, especially those close to the ground.

In order to conserve mass, we have set the orography at the forcing boundaries to a constant. Although it worked well in this study, this can introduce numerical error. We have tested the alternative method of pressure adjustment. But when using the real orography at the boundaries combined with the hydrostatic pressure adjustment, the pressure dropped with time significantly, indicating a lose of mass. However, this method should be looked at more closely and other techniques could be developed for this problem as well.

The model was driven by a coarse resolution UM model. Alternative sources of forcing data, such as the local radiosonde data, should also be explored.

Appendix A : Example idealised namelist

```
& IDEALISE
    L_idealised_data                = .true.        ! Using UM in idealised mode
    L_initialise_data               = .true.        ! Set up idealised initial conditions
    surface_type                    = 10            ! use orography defined in the dump
    grid_number                     = 10            ! defined in dump
    height_domain                   = 39253.2727    ! Height of top of domain
    tprofile_number                 = 9             ! Use temperature profile in namelist
    qprofile_number                 = 9             ! Use rel. hum. profile in namelist
    uvprofile_number                = 9             ! Use u,v wind profile in namelist
    theta_surface                   = 279.5577      ! Set initial surface temperature (K)
    p_surface                       = 101726.2812   ! Set initial surface pressure (Pa)
    f_plane                         = 0.0           ! Set f plane to 0.0 latitude
    L_rotating                      = .true.        ! Normal Earth's rotation
    L_trivial_trigs                 = .true.        ! Cartesian grid
    L_perturb                       = .false.       ! Perturb lowest level temperature
    perturb_factor                  = 0.5           ! Maximum temperature perturbation
    L_force                         = .false.       ! Relax back to initial wind profile
    first_constant_r_rho_level_new  = 38
    L_fixed_lbcs                    = .true.
    L_force_lbc                     = .true.
    L_fix_lbc_z                     = .true.
    L_pforce                        = .true.

    z_orog = 97.091873          ! z_orog = 86.58285315324295
    hf = 7000.000               ! height below data to be streched !101
    hs = 118.000000             ! height in model below streched date are used
    num_profile_data = 39       ! No. of pts in the vertical profile

   ! Height of data points (metres)
zprofile_data =
 0.0,             1.170922E+02,  1.770932E+02,  2.770910E+02,  4.170933E+02,
 5.970925E+02,    8.170922E+02,  1.077093E+03,  1.377090E+03,  1.717092E+03,
 2.097090E+03,    2.517094E+03,  2.977093E+03,  3.477090E+03,  4.017091E+03,
 4.597093E+03,    5.217092E+03,  5.877091E+03,  6.577091E+03,  7.317092E+03,
 8.097093E+03,    8.917092E+03,  9.777091E+03,  1.067709E+04,  1.161709E+04,
 1.259709E+04,    1.361709E+04,  1.467789E+04,  1.579173E+04,  1.697240E+04,
 1.823572E+04,    1.960010E+04,  2.108728E+04,  2.272317E+04,  2.455538E+04,
 2.668073E+04,    2.931617E+04,  3.300579E+04,  3.935193E+04,

   ! Temperature (K)
tprofile_data = 2.795577E+02,
```

```
 2.795577E+02,   2.808932E+02,   2.818462E+02,   2.833717E+02,   2.846464E+02,
 2.855891E+02,   2.866188E+02,   2.869434E+02,   2.894238E+02,   2.919236E+02,
 2.930661E+02,   2.966796E+02,   2.989400E+02,   3.006767E+02,   3.021052E+02,
 3.045793E+02,   3.072531E+02,   3.081942E+02,   3.091346E+02,   3.112961E+02,
 3.129896E+02,   3.161131E+02,   3.231278E+02,   3.319958E+02,   3.469096E+02,
 3.647008E+02,   3.818450E+02,   4.012228E+02,   4.229605E+02,   4.462943E+02,
 4.761691E+02,   5.110641E+02,   5.501741E+02,   5.977263E+02,   6.605625E+02,
 7.528356E+02,   9.151451E+02,   1.195256E+03,

   ! Relative humidity (%/100)
qprofile_data = 5.308241E-03,
 5.308241E-03,   5.373833E-03,   4.716490E-03,   3.933256E-03,   3.837728E-03,
 3.546574E-03,   3.198445E-03,   2.627237E-03,   1.835829E-03,   1.976972E-03,
 2.391581E-03,   9.308245E-04,   3.158748E-04,   2.569065E-04,   3.678338E-04,
 5.278302E-04,   2.580021E-04,   1.787999E-04,   1.300800E-04,   1.158127E-04,
 7.298523E-05,   3.965683E-05,   1.628280E-05,   2.447504E-06,   2.381292E-06,
 2.771870E-06,   2.779633E-06,   2.667065E-06,   2.456541E-06,   2.691569E-06,
 2.902741E-06,   2.890062E-06,   2.890763E-06,   2.992768E-06,   3.000000E-06,
 3.000000E-06,   2.944968E-06,   3.000000E-06,

   ! Westerly wind component
uprofile_data = 0.0,
-1.864494E+00,  -3.222435E+00,  -3.545581E+00,  -2.743948E+00,  -3.441373E+00,
-3.592603E+00,  -4.113445E+00,  -4.581111E+00,  -4.930197E+00,  -3.776934E+00,
-2.236473E+00,  -1.225782E+00,   -3.152271E-01,   -1.198744E-01,  -1.325715E+00,
 -7.637345E-01,    2.113028E-01,    9.045188E-01,    8.236198E-01,    6.859143E-01,
 -8.339107E-01,   -5.451283E-01,   -3.360995E-01,   3.270926E+00,   3.511322E+00,
 8.347032E+00,   7.896582E+00,   8.101352E+00,   1.169186E+01,   1.366478E+01,
 1.655556E+01,   1.962451E+01,   2.212250E+01,   2.628025E+01,   3.160495E+01,
 4.012127E+01,   5.464552E+01,   7.149031E+01,

   ! Southerly wind component
vprofile_data = 0.0,
   9.385707E-02,    7.260948E-01,   2.063607E+00,   1.373851E+00,  -2.733501E-01,
-1.046092E+00,  -1.195905E+00,  -1.468042E+00,  -8.837835E-01,    1.999336E-01,
 3.067045E+00,   3.910264E+00,   4.697858E+00,   5.847753E+00,   6.962871E+00,
 8.353214E+00,   1.166824E+01,   1.380088E+01,   1.475185E+01,   1.390356E+01,
 1.306253E+01,   1.304229E+01,   1.692762E+01,   1.823901E+01,   1.534847E+01,
 6.639966E+00,   5.390640E+00,   6.824551E+00,   5.468454E+00,   4.036940E+00,
 3.945456E+00,   2.597843E+00,   2.193772E+00,   2.462354E+00,   2.008239E+00,
 3.765017E+00,   7.437796E+00,   1.767334E+01,

    pforce_option = 0,             ! 0 no, 1 incre., 2 relax, 3 reset
    num_pforce_times = 13,         ! includes t = 0
    pforce_time_interval = 3600.,  ! 60 minutes

   p_surface_data =
```

101728., 101725., 101729., 101758., 101793.,
101766., 101715., 101681., 101664., 101639.,
101645., 101665., 101675.,

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num_tforce_levels = 39, ! includes z = 0 and z = 40000.
num_tforce_times = 2, ! includes t = 0
tforce_time_interval = 3600., ! 60 minutes

z_tforce_data =
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5.970925E+02, 8.170922E+02, 1.077093E+03, 1.377090E+03, 1.717092E+03,
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4.597093E+03, 5.217092E+03, 5.877091E+03, 6.577091E+03, 7.317092E+03,
8.097093E+03, 8.917092E+03, 9.777091E+03, 1.067709E+04, 1.161709E+04,
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2.930661E+02, 2.966796E+02, 2.989400E+02, 3.006767E+02, 3.021052E+02,
3.045793E+02, 3.072531E+02, 3.081942E+02, 3.091346E+02, 3.112961E+02,
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293.364960, 297.077026, 299.098236, 300.589203, 302.278564,
305.196472, 307.252808, 308.179169, 309.181305, 311.497101,
313.427155, 316.735504, 323.134857, 331.019470, 344.909027,
363.785767, 381.745911, 400.807892, 422.137756, 447.079224,
476.785400, 512.056030, 551.920654, 598.966980, 660.129822,
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qforce_option = 0,
num_qforce_levels = 39, num_qforce_times = 2,
qforce_time_interval = 3600.,

z_qforce_data =

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2.097090E+03, 2.517094E+03, 2.977093E+03, 3.477090E+03, 4.017091E+03,
4.597093E+03, 5.217092E+03, 5.877091E+03, 6.577091E+03, 7.317092E+03,
8.097093E+03, 8.917092E+03, 9.777091E+03, 1.067709E+04, 1.161709E+04,
1.259709E+04, 1.361709E+04, 1.467789E+04, 1.579173E+04, 1.697240E+04,
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2.668073E+04, 2.931617E+04, 3.300579E+04, 3.935193E+04,

qforce_data =
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2.391581E-03, 9.308245E-04, 3.158748E-04, 2.569065E-04, 3.678338E-04,
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2.902741E-06, 2.890062E-06, 2.890763E-06, 2.992768E-06, 3.000000E-06,
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2.680566E-04, 2.357634E-04, 4.240277E-04, 4.629243E-04, 1.956207E-04, 1.566621E-04,
1.425362E-04, 1.134454E-04, 6.274329E-05, 3.498433E-05, 1.712276E-05, 3.881700E-06,
2.308944E-06, 2.788201E-06, 2.722704E-06, 2.637922E-06, 2.549153E-06, 2.929352E-06,
2.880406E-06, 2.877095E-06, 2.888441E-06, 2.999999E-06, 3.000000E-06, 2.993709E-06,
2.893967E-06, 3.000000E-06, 61*0.000,

uvforce_option = 0,
newtonian_timescale = 30.
uvforce_time_interval = 3600.,
num_uvforce_levels = 40, num_uvforce_times = 2,

z_uvforce_data =
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1.907092E+03, 2.307092E+03, 2.747092E+03, 3.227092E+03, 3.747092E+03,
4.307092E+03, 4.907092E+03, 5.547092E+03, 6.227092E+03, 6.947092E+03,
7.707092E+03, 8.507092E+03, 9.347092E+03, 1.022709E+04, 1.114709E+04,
1.210709E+04, 1.310709E+04, 1.414749E+04, 1.523479E+04, 1.638209E+04,
1.760409E+04, 1.891789E+04, 2.034369E+04, 2.190519E+04, 2.363929E+04,
2.561809E+04, 2.799849E+04, 3.116099E+04, 3.617809E+04, 3.900000E+04,

uforce_data = 0.0,

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-2.209404E+00, -1.258525E+00, -4.353354E-01, -3.245327E-01, -1.489800E+00,
-7.963766E-01, 2.471074E-01, 9.060343E-01, 9.352813E-01, 8.044990E-01,
-1.028512E+00, -1.043620E+00, -6.245314E-01, 3.035080E+00, 3.289554E+00,
8.264272E+00, 7.816112E+00, 8.063833E+00, 1.162338E+01, 1.367857E+01,
1.660197E+01, 1.956231E+01, 2.206749E+01, 2.623844E+01, 3.151458E+01,
4.003981E+01, 5.469696E+01, 7.152375E+01, 7.152375E+01, 60*0.000,
0.0,
-1.952898, -3.607795, -3.792562, -3.743653, -5.128597,
-5.400796, -5.564497, -5.331975, -5.398153, -4.346927,
-1.913170, -1.430455, -0.728601, -0.254574, -1.066668,
-0.411099, -0.010237, -0.095442, 0.051309, 0.139251,
-0.464639, 1.209978, 0.902546, 3.607064, 4.609193,
6.838840, 6.275325, 8.695741, 12.546258, 14.242673,
18.114552, 20.299648, 22.168509, 25.896109, 31.054619,
40.226326, 53.927082, 68.821579, 68.821579, 60*0.000,

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3.119998E+00, 4.002728E+00, 4.814854E+00, 6.009938E+00, 7.160545E+00,
8.477488E+00, 1.170274E+01, 1.378663E+01, 1.480653E+01, 1.395963E+01,
1.320322E+01, 1.320953E+01, 1.709827E+01, 1.830372E+01, 1.553143E+01,
6.831294E+00, 5.489661E+00, 6.943574E+00, 5.492064E+00, 4.114526E+00,
4.011350E+00, 2.652647E+00, 2.278372E+00, 2.475308E+00, 1.970878E+00,
3.772041E+00, 7.484960E+00, 1.766010E+01, 1.766010E+01, 60*0.000,
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0.180028, 0.794683, 1.908802, 0.713571, -0.457675,
-1.175478, -1.446797, -1.513457, -0.920161, 0.016492,
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3.560122, 2.320489, 1.686738, 1.131762, 0.738851,
1.874068, 6.607485, 15.060588, 15.060588, 60*0.000,

&END